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Substantial progress has been made in several research area. For example, a new class of neural networks has been developed which are defined by high-dimensional nonlinear dynamics systems that operate at multiple time scales. They are designed to carry out fast, stable autonomous learning of recognition codes and multidimensional maps in response to arbitrary sequences of input patterns. The new neural networks architecture, called ARTMAP, autonomously learns to classify many, arbitrarily ordered vectors into recognition categories based on predictive success. In other research, these investigators developed a new model of temporal prediction that is based upon analysis of how animals and humans learn to time their actions to achieve desired goals. Research was also conducted on the neural dynamics of speech filtering and segmentations; measurement theory; and temporal predictions reinforcement learning, and autonomous credit assignment.

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COMPUTER AND MATHEMATICAL MODELLING OF MASSIVELY PARALLEL ARCHITECTURES FOR SELF-ORGANIZING NEURAL PATTERN RECOGNITION MACHINES

January 1, 1990—June 30, 1992

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PROJECT SUMMARIES

Below are summarized five of the several areas on which significant progress has been made.

1. Autonomous Learning, Pattern Recognition, and Prediction [Articles 9, 10, and 11]

An important open problem in applied mathematics and technology is to design autonomous systems capable of learning to recognize and predict nonstationary data in which mixtures of rare, frequent, and unexpected events may occur. In order to cope with rare events, fast learning is needed. Fast learning can, however, destabilize many learning schemes. In order to cope with nonstationary combinations of rare and frequent events, different degrees of generalization, or code compression, must be learnable by a single system. Many learning schemes cannot simultaneously operate at multiple scales of coarseness. In order to rapidly learn different predictions in response to rare events than to a cloud of similar frequent events in which they are embedded, predictive feedback about success or failure needs to operate in real-time using only local operations to separate the rare exemplar from the frequent cloud. Many learning schemes that use predictive feedback can only operate in an off-line mode, or need to use slow learning, or are computed using non-local operations.

The present work introduces a new class of real-time neural networks that overcome all of these problems. These neural networks are defined by high-dimensional nonlinear dynamical systems that operate at multiple time scales. They are designed to carry out fast, stable, autonomous learning of recognition codes and multidimensional maps in response to arbitrary sequences of input patterns. In order to learn quickly and stably in response to a nonstationary input stream, the networks incorporate operations that were derived from an analysis of human cognition, and that have been used to explain and predict many behavioral and neural data. These operations include the learning of abstractions and expectations, paying attention, hypothesis testing, memory search, novelty detection, and confidence. Dynamical systems that embody these operations are often called Adaptive Resonance Theory, or ART, networks because such a network enters a resonant state when it pays attention to data about which it will learn.

The new neural network architecture, called ARTMAP, autonomously learns to classify arbitrarily many, arbitrarily ordered vectors into recognition categories based on predictive success. This supervised learning system is built up from a pair of ART modules (ART_a and ART_b) that are capable of self-organizing stable recognition categories in response to arbitrary sequences of input patterns. During training trials, the ART_a module receives a stream $\{a^{(p)}\}$ of input patterns, and ART_b receives a stream $\{b^{(p)}\}$ of input patterns, where $b^{(p)}$ is the correct prediction given $a^{(p)}$. These ART modules are linked by an associative learning network and an internal controller that ensures autonomous system operation in real time. During test trials, the remaining patterns $a^{(p)}$ are presented without $b^{(p)}$, and their predictions at ART_b are compared with $b^{(p)}$. Tested on a benchmark machine learning database in both on-line and off-line simulations, the ARTMAP system learns orders of magnitude more quickly, efficiently, and accurately than alternative algorithms, and achieves 100% accuracy after training on less than half the input patterns in the database.

ARTMAP achieves these properties by using an internal controller that realizes a new Minimax Learning Rule, which conjointly maximizes predictive generalization and minimizes predictive error by linking predictive success to category size on a trial-by trial-basis, using only local operations. This computation increases the vigilance parameter ρ_a of ART_a by the minimal amount needed to correct a predictive error at ART_b. Parameter ρ_a calibrates the minimum confidence that ART_a must have in a category, or hypothesis, activated by an input $\mathbf{a}^{(p)}$ in order for ART_a to accept that category, rather than search for a better one through an automatically controlled process of hypothesis testing. Parameter ρ_a is compared with the degree of match between $\mathbf{a}^{(p)}$ and the top-down learned expectation, or prototype, that is read-out subsequent to activation of an ART_a category. Search occurs if the degree of match is less than ρ_a. ARTMAP is thus a type of self-organizing expert system that calibrates the selectivity of its hypotheses based upon predictive success. As a result, rare but important events can be quickly and sharply distinguished even if they are similar to frequent events with different consequences.

Between input trials ρ_a relaxes to a baseline vigilance $\overline{\rho_a}$. When $\overline{\rho_a}$ is large, the system runs in a conservative mode, wherein predictions are made only if the system is confident of the outcome. Very few false-alarm errors then occur at any stage of learning, yet the system reaches asymptote with no loss of speed. Because ARTMAP learning is self-stabilizing, it can continue learning one or more databases, without degrading its corpus of memories, until its full memory capacity is utilized.

2. Global Analysis, Parallel Computation, and Content Addressable Memory [Articles 17 and 18]

An important problem in parallel computation, control theory, and content addressable memory is to *construct* dynamical systems which converge to a prescribed set of equilibria or oscillations, and to *only* these dynamical modes. The former problem includes the problem of designing a global CAM as a special case.

In this work, two new methods for constructing systems of ordinary differential equations realizing any fixed finite set of equilibria in any fixed finite dimension are introduced; no spurious equilibria are possible for either method. By using the first method, one can construct a system with the fewest number of equilibria, given a fixed set of attractors.

Using a strict Lyapunov function for each of these differential equations, a large class of systems with the same set of equilibria is constructed. A method of fitting these nonlinear systems to trajectories is proposed. In addition, a general method which will produce an arbitrary number of periodic orbits of shapes of arbitrary complexity is also discussed.

A more general second method is given to construct a differential equation which converges to a fixed given finite set of equilibria. This technique is much more general in that it allows this set of equilibria to have any of a large class of indices which [illegible] the Morse inequalities. It is clear that this class is not universal, because there is a large class of additional vector fields with convergent dynamics which cannot be constructed by the above method.

The easiest way to see this is to enumerate the set of Morse indices which can be obtained by the above method and to compare this class with the class of Morse indices of arbitrary differential equations with convergent dynamics. The former set of indices are a proper subclass of the latter; therefore, the above construction cannot be universal. In general, it is a difficult open problem to construct a specific example of a differential equation with a given fixed set of equilibria, permissible Morse indices, and permissible connections between stable and unstable manifolds.

A strict Lyapunov function is given for this second case as well. This strict Lyapunov function as above enables construction of a large class of examples consistent with these more complicated dynamics and indices. The determination of all the basins of attraction in the general case for these systems remains to be accomplished.

In particular, a simple feedback system with an elementary coupling rule has been constructed which generates all the possible qualitative dynamics for a convergent differential equation; i.e., generates all the possible Morse Indices which a system with convergent dynamics produces. Strict Lyapunov functions have been obtained for these systems as well, so that very large families of systems with similar dynamics can be constructed.

Finally, a means to approximate arbitrary sets of nested periodic orbits with a specified set of Morse Indices has been discussed. It is shown that these orbits can be approximated to any precision in that finite sets of data on each of these orbits can be exactly fit.

This has many applications. In particular, the work can be used to construct a theory of "nonlinear" regression for differential equations whereby nonlinear dynamics curve fits can be specified and an underlying law which fits the data can be specified.

Such a theory can be used to produce a general analog design of digital components. It indicates a method whereby general analog hardware can be used to do digital transductions.

Preliminary results indicate that Grossberg's (1980) Adaptation Level Theorem can be extended to a system with multiple state-dependent adaptation levels. It is noteworthy that the class of systems which are treated by this system include a subclass of the classical Lure-Postnikov and Popov systems studied in optimal control theory.

This theory promises to extend the domain to which the stability theory of classical control systems can be applied.

3. Temporal Prediction, Reinforcement Learning, and Autonomous Credit Assignment [Articles 1 and 22]

An important problem in the real-time problem solving of a human operator or machine concerns the proper temporal scheduling of actions so that they occur when they are needed, and not at inopportune times. The present work develops a new model of temporal prediction that is based upon an analysis of how animals and humans learn to time their actions to achieve desired goals. The problem that is being solved may be summarized as follows.

Many goal objects may be delayed subsequent to the actions that elicit them, or the environmental events that signal their subsequent arrival. Humans and many animal species can learn to wait for the anticipated arrival of a delayed goal object, even though its time of occurrence can vary from situation to situation. Such behavioral timing is important in the lives of animals which can explore their environments for novel sources of gratification. For example, if an animal could not inhibit its exploratory behavior, then it could starve to death by restlessly moving from place to place, unable to remain in one place long enough to obtain food there. On the other hand, if an animal inhibited is exploratory behavior for too long, waiting for an expected source of food to materialize, then it could starve to death [illegible]

Thus the animal's task is to accurately time the *expected* delay of a goal object based upon its previous experiences in a given situation. It needs to balance between its exploratory behavior aimed at searching for novel sources of reward, and its consummatory behavior aimed at acquiring expected sources of reward. To effectively control this balance, the animal or machine needs to be able to suppress its exploratory behavior and focus its attention upon an expected source of reward at around the time that the expected delay transpires for acquiring the reward.

This type of timing calibrates the delay of a single behavioral act, rather than organizing a correctly timed and speed-controlled sequence of acts. Suppose, for example, that an animal typically receives food from a food magazine two seconds after pushing a lever, and that the animal orients to the food magazine right after pushing the lever. When the animal inspects the food magazine, it perceives the nonoccurrence of food during the subsequent two seconds. These nonoccurrences disconfirm the animal's sensory expectation that food will appear in the magazine. Because the perceptual processing cycle that processes this sensory information occurs at a much faster rate than two seconds, it can compute this sensory disconfirmation many times before the two second delay has elapsed.

The central issue is: What spares the animal from erroneously reacting to these *expected nonoccurrences* of food during the first two seconds as predictive failures? Why does the animal not immediately become frustrated by the nonoccurrence of food and release exploratory behavior aimed at finding food somewhere else? If the animal does wait, but food does not appear after the two seconds have elapsed, why does the animal then react to the *unexpected nonoccurrence* of food by becoming frustrated and releasing exploratory behavior?

The present model shows how the timing mechanism can inhibit, or *gate*, a process whereby sensory mismatches with learned expectations trigger the orienting and reinforcement mechanisms that would otherwise reset the animal's attentional focus, negatively reinforce its previous consummatory behavior, and release its exploratory behavior. The process of registering these sensory mismatches or matches is not itself inhibited. For example, if the food happened to appear earlier than expected, the animal could still perceive it and eat. Thus the sensory matching process is not inhibited by the timing mechanism. Instead, the effects of sensory mismatches upon processes of memory reset and reinforcement are inhibited.

This inhibitory action is assumed to be part of a more general competition that occurs between the motivational, or arousal, sources that energize different types of behavior. The posited inhibitory action is from the motivational sources of consummatory behaviors to the motivational sources of orienting and exploratory behaviors. The consummatory motivational sources are also assumed to be in mutual competition, enabling only the strongest combinations of sensory, reinforcing, and homeostatic signals to control observable behaviors. Thus the posited competition is a special case of the general hypothesis that the output signals from all motivational sources compete for the control of observable behaviors. This competition regulates the decision process whereby potentially competing events can be scheduled to conjointly satisfy the constraints imposed by multiple goals.

From a neurobiological perspective, the results offer a solution to several basic problems about biological memory. The model is called a START model because it shows how a Spectral Timing process can modulate ART mechanisms. The combination of these mechanisms suggests how reinforcement learning is adaptively timed and modulates the course of recognition learning, attention switching, memory search, selective forgetting, and the timing of goal-oriented actions. The model suggests how NMDA receptors in the dentate-CA3 region of the hippocampus may participate in learning to adaptively time reinforcement learning, and helps to explain the complex pattern of changes in trace conditioning, delay conditioning, and reversal conditioning that are caused by hippocampal ablations. It is suggested that conditioning may potentiate coordinated processes of presynaptic transmitter produc- [illegible] behaviors. Convergence of dentate cells on CA3 pyramidal cells is suggested to create a collective adaptively timed signal that no single dentate cell can generate by itself.

The model suggests neural mechanisms for several distinct types of learning: learning of adaptive timing; reinforcement learning, including emotional conditioning; incentive motivational learning, to help focus attention and energize behavioral responses; motor learning of discrete adaptive responses; and recognition learning. In particular, the model distinguishes between cerebellar influences on motor learning and hippocampal influences on adaptive timing of reinforcement learning. The model clarifies how damage to the hippocampal formation eliminates attentional blocking and causes symptoms of medial temporal amnesia. It suggests how normal acquisition of subcortical emotional conditioning can occur after cortical ablation, even though extinction of emotional conditioning is severely retarded by cortical ablation. The model also clarifies how the anatomical sites and functional properties of emotional conditioning and conditioning of adaptive timing differ.

Model interactions between sustained and transient cells help to explain how increasing the duration of an unconditioned stimulus increases the amplitude of emotional conditioning, but does not change conditioned timing; and how an increase in the intensity of a conditioned stimulus "speeds up the clock", but an increase in the intensity of an unconditioned stimulus does not. Computer simulations of the model fit parametric conditioning data from the rabbit nictitating membrane paradigm, including a Weber law property, inverted U property, and anomalous shift and amplification in the adaptively timed data at large interstimulus intervals (ISIs). Both primary and secondary adaptively timed conditioning are simulated, as are data concerning conditioning using multiple ISIs, gradually or abruptly changing ISIs, partial reinforcement, and multiple stimuli that lead to time-averaging of responses. Neurobiologically testable predictions are made to facilitate further tests of the model.

4. Neural Dynamics of Speech Filtering and Segmentation [Articles 1 and 20]

A different type of temporal processing is being analyzed in our work on early speech filtering and coherent speech segmentation. These results are aimed at understanding the specialized filters that have evolved to help disambiguate coarticulated sounds, such as vowels and consonants, under noisy and unreliable conditions. At a later processing stage, both forward-acting and backward-acting contextual effects can disambiguate noisy sounds, via a coherent segmentation and completion process, even in cases where no obvious speech boundaries exist.

A set of sustained and transient detectors have been constructed which can partially disambiguate coarticulated consonants and vowels. The sustained detectors are sensitive primarily to vocalic phonemic segments. The transient detectors are primarily sensitive to different aspects of speech transitions such as the onset or offset of consonantal bursts, the offset of consonants, and frication stimuli. These detectors can be used to detect differing phonemic qualities and as initial detectors of various consonantal types so as to be able to use more specialized detectors to precisely identify a specific type of stop or vowel.

We are also interested in formulating a general theory of auditory object recognition. Such a theory would explain the ability to segregate different auditory objects as part of the auditory scene. One major (perhaps the dominant factor) in separating two auditory objects is pitch. We have thereby been constructing a model, the Spinet (Spatial Pitch Network) model of pitch perception, which unifies and explains much of the pitch data in the literature. This model is being incorporated in a more general model of auditory object recognition.

Our work on this project should help to solve some of the types of radar and speech processing problems where methods like dynamic programming fails. We have started to test these new filter models on databases such as TIMIT and ISOLET, and on data such as phonemic restoration and backward completion effects.

Remarkably, the models in all of the projects can be viewed as ART architectures which share many basic processing operations, but have been specialized in a principled manner to cope with the constraints of different task domains. In this sense, all the results contribute to a general theory of intelligent information processing by dynamical systems that carry out a biological style of parallel computation.

5. Measurement Theory [Articles 16, 17, and 18]

Significant progress has recently been made in the study of non-associative concatenation structures of two variables. In recent work, Cohen has completed the classification of general non-associative idempotent operations begun by Cohen and Narens (1979) and Luce and Narens (1985) using the structure of the automorphism group of these operations. In addition, weakly positive concatenation structures have been completely classified under very mild solvability and unboundedness constraints. Such work is important in clarifying the nature of differing scale types such as ordinal, interval, and ratio scales, when it is possible to construct a subjective scale.